

# A study of external heat exchange between the vibrofluidized bed surface and the coolant gas in devices used for spent nuclear fuel regeneration

B G Sapozhnikov<sup>1</sup>, A M Gorbunova, Yu O Zelenkova, N P Shiriaeva

Ural Federal University, Ural Energy Institute, Yekaterinburg, RUSSIA

<sup>1</sup> [bgs0910@mail.ru](mailto:bgs0910@mail.ru)

**Abstract.** The oxidative recrystallization of spent nuclear fuel running in the vibrofluidized bed mode requires a continuous supply or removal of heat, which can be performed using various techniques. The most advantageous of these is supplying a coolant gas over the surface of the vibrofluidized bed. However, the available information about such heat exchange processes is limited. External heat exchange between the surface of the vibrofluidized bed and the blown coolant gas was investigated using fuel simulators, which construction was based on narrow-fraction electrocorundum exhibiting the particle size of  $d_p = 0,07 \div 1,25$  mm in a device with the diameter of 100 mm and the height of 160 mm according to a stationary technique. The data on the influence of the coolant flow, the amplitude and frequency of vibration, as well as the particle size of the dispersed material were obtained. In order to explain the results obtained, we used data on the pulsations of the gas flow velocities occurring in the vibrofluidized bed and depending on the parameters listed above.

## 1. Introduction

In order to be utilized further, spent nuclear fuel should be recycled first. Reprocessing of such fuel via oxidative recrystallization [1] run in the vibrofluidized bed mode [2, 3] is believed to be the most prospective approach. The advantages of this approach involve timely removal of reaction products, crushing and shaking of the fuel shielded by a shell, transportation of oxidized fuel and construction materials for subsequent recycling. In terms of construction, a device for fuel reprocessing can be build in the form of a horizontal trench or a tube [4], as well as a vertical vibrator equipped with two concentric spiral trays [5].

Atmospheric air can be simultaneously used as a coolant during the supply or removal of heat and in the oxidative recrystallization process. Numerous approaches to the supply or removal of heat into the vibrofluidized bed are known. Certain advantages arise when a coolant is blown over the bed of the bulk material under treatment [6]. In this case, the properties of the vibrofluidized bed are determined mainly by the vibration parameters, particle size, height of the bed, and are almost independent of the gas flow rate. However, information about such heat exchange processes is limited.

## 2. Experimental setup and its approbation

When a gas is blown over the free surface of the vibrofluidized bed, the heat and gas exchange occurs due to self-ventilation resulting from unsteady gas flows that arise in the bed and penetrate into the freeboard [6]. However, under the conditions of stable gas consumption and constant heat supply or removal, the heat exchange process can be considered as quasi-stationary. Therefore, we studied the heat exchange between a vibrofluidized bed and a blown gas using a stationary technique and the Newton-Richman equation

$$Q = \alpha \cdot (t_A - t_{B1}) \cdot F, \quad (1)$$

In order to achieve this, we developed and manufactured an experimental setup.



The main element of the setup was a vertical cylinder made of plexiglas with the internal diameter of 100 mm and the height of 160 mm. This cylinder was loaded with a bulk material such as narrow-fraction electrocorundum exhibiting the particle sizes of  $d_p=0.07, 0.16, 0.32, 0.63$  and 1.25 mm.

The heights of the bed  $H_0$  were 80 and 120 mm. The vessel was rigidly fastened to the vibrating table that was to produce vertically directed oscillates with a frequency  $f$  ranging from 30 to 60 Hz and an amplitude  $A$  of up to 2 mm. The relative vibration acceleration  $K = A*\omega^2/g$  did not exceed 15.

Air measured by a flowmeter and pre-heated by an electric heater was blown through the chamber above the bed using a fan. The internal diameter of the inlet and outlet nozzles in the chamber above the bed was 6 mm. The volumetric flow rate of air  $V_A$  varied from 0.5 to 1.1 m<sup>3</sup> / h. The lid and side walls of the vessel were covered with thermal insulation. The bottom of the vessel was cooled by running water.

The air flow rate  $V_A$ , air temperature in the freeboard chamber  $t_A$ , differences in the air temperature at the inlet and outlet from the freeboard chamber  $\delta t_A$ , as well as temperatures in the upper active part of the bed and in its several horizontal sections were measured. Copper-constantan thermocouples connected via a switch to a digital millivoltmeter were used. The batteries of three thermocouples were used to obtain the averaged data on the temperature in the horizontal sections of the bed. The air flow and its heating were regulated by autotransformers. In all the experiments, the height of the freeboard chamber remained unchanged and was 40 mm.

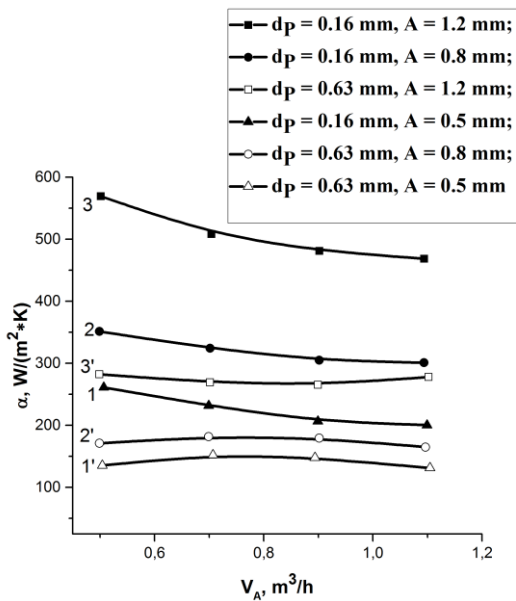
The investigation of the temperature distribution along the height of the bed showed [7] that the gas temperature  $t_A$  in the freeboard chamber remained almost unchanged due to good mixing caused by the air flow moving through the freeboard chamber and due to self-ventilation penetrating into the chamber. At the interface, the gas temperature dropped abruptly to a temperature  $t_{B1}$  in the region near surface  $h_1$ . In this region, as had been shown by sounding [7], the temperature almost remained unchanged. The temperature difference  $\Delta t_B$  in the core of the bed  $h_0$  ranged from 0.6 to 4.1°C depending on the vibration parameters. In addition, an almost gradientless zone  $h_2$  was again observed in the lower part of the bed. Given the complexity of determining the surface of particles in the upper active zone  $h_1$ , the heat transfer coefficient  $\alpha$  in equation (1) was referred to the unit surface of the bed mirror  $F$ . The mean quadratic error in determining the heat transfer coefficients  $\alpha$  ranged from 4 to 9%.

### 3. Results

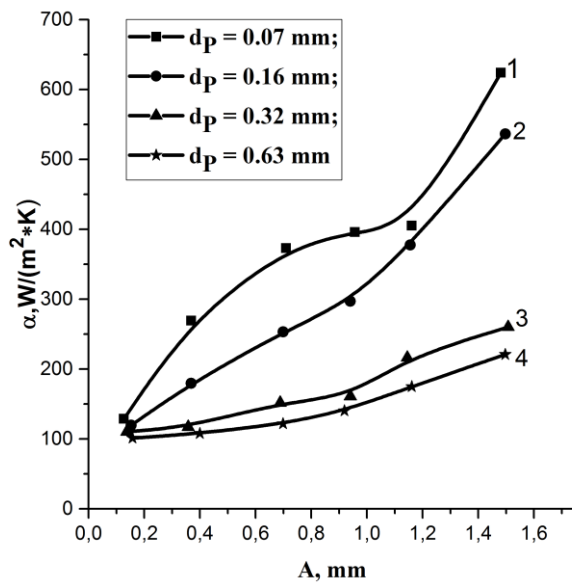
#### 3.1. Influence of gas coolant flow and vibration amplitude

Figure 1 demonstrates the experimental data on the effect that gas flow has on heat transfer. It is seen that the coefficients of heat transfer to the layer of fine particles ( $d_p \leq 0.16$  mm, curves 1-3) decrease slightly with an increase in air flow; however, the coefficients of the heat transfer to the layer of medium- and coarse-grained particles ( $d_p \geq 0.32$  mm, curves 1'-3') almost remain unchanged. In addition, an increase in the vibration amplitude results in an increase in  $\alpha$  coefficients, other factors being equal. The curves corresponding to the larger values of  $A$  are located higher in Figure 1.

In order to explain the established regularities, we used information on the effect of vibration parameters on the hydrodynamics of the vibrofluidized bed. According to [8], when the vibration amplitude of pulsation grows, the gas streams velocities, which arise in the vibrofluidized bed and contribute to the chaotic motion of the disperse medium, increase steadily both inside the bed and near its free surface. A more intense heat exchange between the bed and the freeboard corresponds to higher velocity pulsations. A more intense heat exchange leads to a corresponding change in the coefficients  $\alpha$ . In turn, the presence of a closed space above the bed leads to an increase in the pressure in the bed, decrease in the velocity pulsations and a slight decrease in the heat exchange intensity. As a result, the intensity of heat transfer demonstrates a slight reduction (Figure 1).



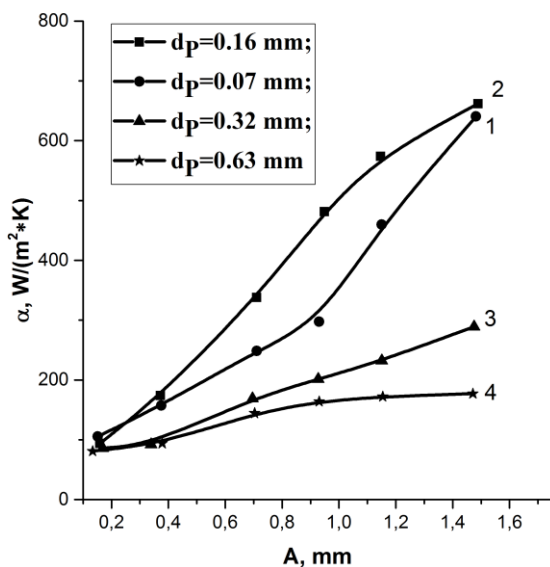
**Figure 1.** Dependence of the heat transfer coefficient  $\alpha$  (between the vibrofluidized bed and the blown air) on air flow rate  $V_A$ :  $H_0 = 120$  mm,  $f = 40$  Hz;  $t_A = 30 - 65^\circ\text{C}$



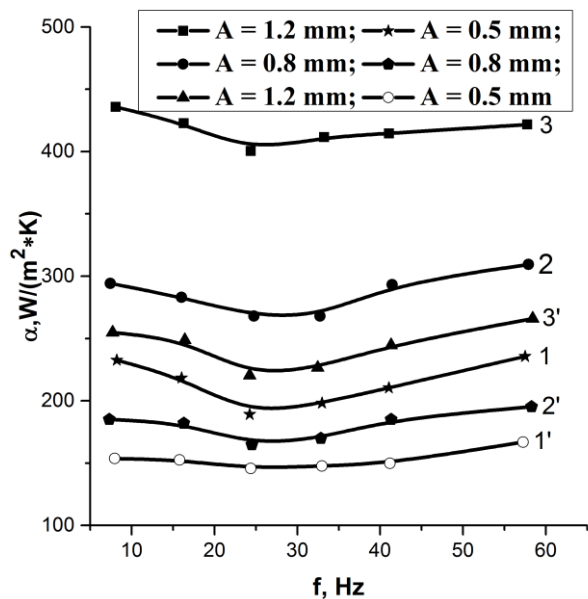
**Figure 2.** Dependence of the heat transfer coefficient  $\alpha$  (between the vibrofluidized bed and the blown air) on the vibration amplitude  $A$ :  $V_A = 0.9$  m<sup>3</sup>/h;  $f = 40$  Hz,  $H_0 = 80$  mm

### 3.2. The influence of vibration frequency and particle size of the bed

Compared to the amplitude, numerous characteristics of the vibrofluidized bed, in particular the external heat and mass transfer coefficients [3], achieve their maximum values. This is largely because resonance phenomena occur at a certain frequency of forced oscillations and at a certain



**Figure 3.** Dependence of the heat transfer coefficient  $\alpha$  (between the vibrofluidized bed and the blown air) on the vibration amplitude  $A$ :  $V_A = 0.9$  m<sup>3</sup>/h;  $f = 50$  Hz,  $H_0 = 120$  mm

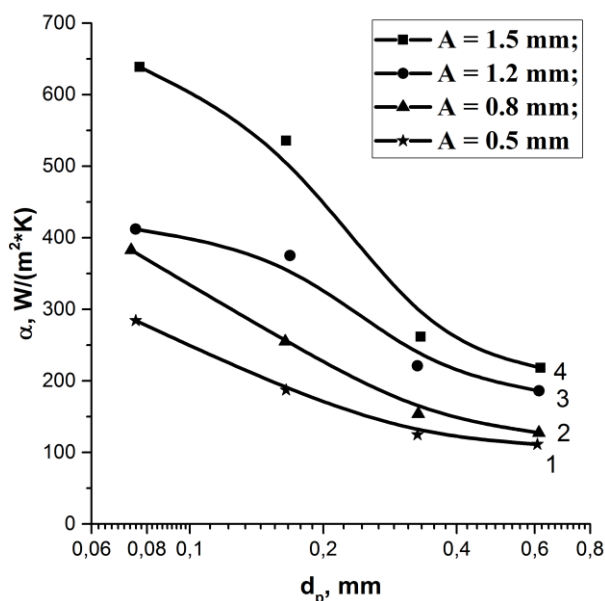


**Figure 4.** Dependence of the heat transfer coefficient  $\alpha$  on the vibration frequency  $f$ :  $V_A = 0.9$  m<sup>3</sup>/h, (1-3) -  $d_p = 0.16$  mm, (1'-3') -  $d_p = 0.32$  mm,  $H_0 = 120$  mm

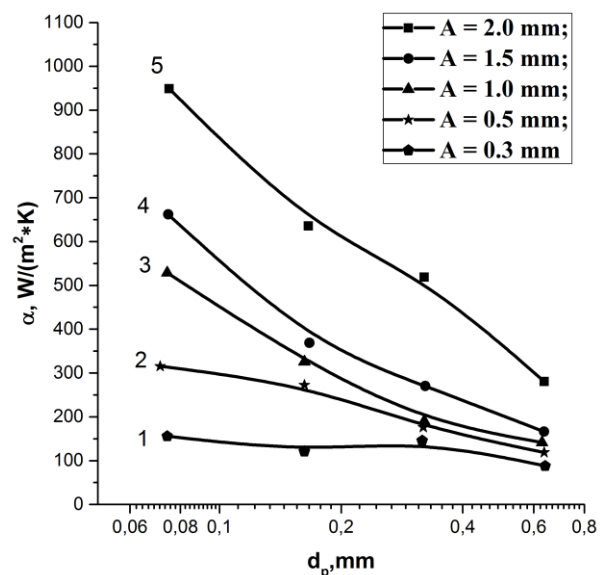
height of the bed [9]. In addition, resonance frequencies were observed to be less than 30 Hz at a backfilling height of  $H_0 \geq 80$  mm. The limited volume of the freeboard slightly increases the resonance frequency. However, in our experiments, the heights of the bed were 80 and 120 mm, and the frequency of vibration varied from 30 to 60 Hz, which corresponds to the over-resonance regimes, with the frequency values being insignificant. This explains the weak dependence of the experimental heat transfer coefficients  $\alpha$  on the vibration frequency, all other conditions being equal (Figure 4).

Curves 1-3 and 1'-3' (Figure 4) demonstrate that, in addition to the amplitude (Figures 2 and 3), the particle size of the bed significantly affects the interphase heat exchange. More detailed data are represented in semilogarithmic coordinates as the dependences  $\alpha = \varphi(d_p)$  (Figures 5, 6). This is due to the fact that the level of interaction between the gas and solid phases depends on the particle size ( $d_p < 1.0$  mm) to a greater extent than on other factors. This level of interaction between the gas and solid phases determines the specific features and intensity of processes in the vibrofluidized bed. Therefore, many authors have focused on the value of  $d_p$  as one of the most important classification characteristics of vibrofluidized beds. For example, in [10] the classification of vibrofluidized beds was proposed on the basis of the particle size variation. Particles were divided into fine ( $d_p = 0.05$ -0.2 mm), medium-grained (0.2-0.5 mm) and coarse (0.5-1.5 mm). This explains that the coefficients  $\alpha$  change with an increase in  $d_p$ .

In the bed of fine particles ( $d_p = 0.07$  and 0.16 mm), as a result of high hydraulic resistance, the vibrating fluidizing is achieved by means of the unsteady filtration of the gaseous medium. This effect is less pronounced for particles with a diameter of 0.16 mm. Therefore, the flowing mode rapidly develops in the bed of particles having a diameter of 0.07 mm (Figures 5, 6). Such a mode is accompanied by ejection of the material into the freeboard at sufficiently high amplitudes, which process leads to anomalously high values of the coefficients  $\alpha$ , reaching 950 W/(m<sup>2</sup>\*K) at  $H_0 = 120$  mm. Under these conditions, an increase in particle size makes the vibrofluidized bed switch from the flowing mode to the suspended one, and then to the piston or vibro-moving mode with a lesser intensity of disperse medium motion, which in turn leads to a decrease in heat transfer coefficients.



**Figure 5.** Dependence of the heat transfer coefficient  $\alpha$  on the bed particle diameter  $d_p$ :  $f = 40$  Hz,  $H_0 = 80$  mm,  $V_A = 0.9$  m<sup>3</sup>/h



**Figure 6.** Dependence of the heat transfer coefficient  $\alpha$  on the bed particle diameter  $d_p$ :  $f = 40$  Hz,  $H_0 = 120$  mm,  $V_A = 0.9$  m<sup>3</sup>/h

Finally, it can be noted that the largest change in the heat transfer coefficients occurs in the beds of particles exhibiting a diameter  $d_p$  ranging from 0.07 mm to 0.32 mm; however, subsequently, the effect of the particle size on the heat exchange becomes significantly weaker (Figures 5, 6). The results obtained can be applied for drying disperse materials as well as for carrying out various thermochemical processes in vibrofluidized bed devices.

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